The Role of Product and Process Innovation in CGE Models of Environmental Policy

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Contribution to the Project

The research paper will give an overview how innovation activities and innovation policy instruments are used in existing studies using a multi-sectoral, multi-country CGE model. Especially, most macro-economic models (which also comprise CGE models) focus on process innovation only and, hence, omit other types of innovation especially product innovation (this also holds for product eco-innovation). The review of the literature will systematically build a inventory of modelling approaches by types of innovation. Hence, research paper relates to wwwforEurope's objectives by summarizing the knowledge how different types of innovation and different types of government incentive to innovate can be included in macro-economic multisector models.

Keywords: CGE models, ecological innovation, economic growth path, green jobs, innovation, innovation policy, social innovation, socio-ecological transition, sustainable growth

Jel codes: O41, O40, O47

The Role of Product and Process Innovation in CGE Models of Environmental Policy

Claudio Baccianti and Andreas Löschel

Abstract

In the last two decades, large scale CGE models used for environmental policy assessment underwent an important upgrade to integrate endogenous technological progress. Nevertheless, several complexities of innovation are still neglected even if they are of primary interest for policymakers. This paper provides a review of the current state of the art in the CGE modelling literature through a special lens. We discuss how existing models deal with different types of innovation (i.e. product and process innovation) and how differences in innovation activities influence modelling results. We also emphasise the implications of product innovation in a multi-sector framework, which has received little attention in the literature.

1 Introduction

In the last two decades the Computational General Equilibrium (CGE) modelling community has worked to overcome one of the main challenges for computational policy analysis: making technological progress endogenous. Most CGE models are used to forecast policy impacts over a quite long time horizon and it is misleading to assume that governmental policies do have neither direct nor indirect effects on research and the adoption of new technologies.

Some comprehensive literature reviews have been published to keep track of this fast-growing field of research. Löschel (2002) is one of the first surveys about applied general equilibrium models with endogenous technological progress. The article classifies existing applied models of environmental policy into different categories and presents not only alternative approaches for endogenising technology but as well different ways to represent exogenous technological progress, still used in several models. It provides a very extensive review of models actively used in policy analysis up to the beginning of the 2000s. Sue Wing (2006) is instead a literature review study that puts more emphasis on summarising the theoretical background underlying the endogenisation of technological progress. One of the major constraints in the further development and application of endogenous technological change models has been the scarcity of empirical support for the calibration of all those new technology functions, i.e. innovation possibility frontiers, that were used in technology modules. Pizer and Popp (2008) answer this need and bridge the state of the art in modelling work with the recent results in the empirical literature. Other recent surveys on endogenous technological change models for environmental policy analysis include Gillingham et al. (2008), Carraro et al. (2010) and Löschel and Schymura (2013).

This paper is not just a survey of the existing literature, for which we refer to the already exhaustive earlier studies for more details. We offer a review of applied modelling of environmental policy with endogenous technological change through a special lens. Previous work has generally overlooked the heterogeneity of innovation activities, which is instead a crucial fact in the microeconomic literature about innovation. We scrutinize and discuss the role that product, process and as well organizational innovation have in existing CGE models with endogenous technological progress. This perspective provides some new interesting insights about drivers of technological progress like R&D investment, learning-by-doing and product-embodied technology. We find that in most of the existing literature the modelling of innovation mostly depicts process innovation. Product innovation plays instead a marginal role for two reasons. First, if product quality is represented as simple product-augmenting technology - that is higher quality enhances the direct productivity of the good, as in Schumpeterian models - then product and process innovation actually deliver equivalent results. Second, there are serious limitations in fully capturing the concept of product quality in modelling work because, for instance, data on (and measures of) product quality are not available. We discuss how the distinction of product and process innovation is actually important under alternative definitions of product quality (i.e. energy efficiency) and we find it to be an interesting line of future research.

Our discussion is structured as follows. In Section 2, we introduce the concept of innovation in general equilibrium models and provide definitions of different types of innovation. In Section 3 we review the theoretical background of CGE models with endogenous technological change, mostly the endogenous growth literature. Section 4 contains a discussion of different families of endogenous CGE model. We analyse how product and process innovation are accounted for in each modelling approach, from the knowledge stock formulation to backstop technologies. Here we argue that in a multi-sector model the distinction between product and process innovation might shed light on interesting mechanisms that were otherwise considered pure technology spillovers. Section 5 concludes.

2 Innovation in General Equilibrium

The simplest way to introduce technological progress in a general equilibrium model is to augment production functions with an exogenous productivity scaling factor, namely a Total Factor Productivity (TFP) variable. Since the earliest literature on economic growth (Solow, 1956, 1957), TFP has been quite effective in dealing with technological progress, as it captures the fact that the development and adoption of new technologies have distinct effects from labour growth and capital accumulation. Technical change releases firms productivity from the limits of decreasing factor returns and it is the most important driver of long-run growth in per capita income. TFP is able to generate this effect in growth models in a quite simple way.

Consider an aggregate production function $F(.)$, twice differentiable, using labour L_t and capital K_t. Aggregate output Y_t is

$$Y_t = A_t F(L_t, K_t), \tag{1}$$

where A_t is an index of the level of technological progress at the aggregate level, representing technological change that does not affect factor proportions. The function F may be interpreted as an indicator of productivity in physical units and A_t the productivity measured in efficiency units. CGE models with exogenous technological change assume that A_t is a deterministic process driven by a growth rate g_{At}, so that $A_{t+1} = (1+g_{At})A_t$. In energy and environmental economics, the exogenous process that depicts patterns of energy productivity is similar to A_t and it is commonly named Autonomous Energy Efficiency Improvements (AEEI, e.g. Nordhaus, 1994, van der Mensbrugghe, 2008, Chateau et al., 2014). Azar and Dowlatabadi (1999) present a review of the early literature on modelling environmental policy. The level and growth rate of variables depicting technological progress are calibrated using empirical estimates or left as a free parameter to be tuned up under alternative scenarios.

This representation has several advantages in terms of model tractability and data availability, and it as well delivers satisfactory outcomes when the policy does not have substantial interaction with innovation over the time horizon of interest. However, the representation of technological change in equation (1) suffers from important drawbacks and limitations. First, in the model innovation cannot respond to policy changes if A_t is exogenous. This assumption is not only unrealistic, it prevents from having one key channel of policy intervention. Endogenous innovation in CGE models comes from the need to account for the response of research to policy changes, for instance the shift of innovation investment across sectors, production inputs and time. Besides plain research subsidies, the introduction of an input tax might attract or reduce innovation activities aiming to save the use of this input in production, as the theory of induced innovation suggests (Jaffe et al., 2003). Environmental policy is an example of how the inducement effects can be crucial to reduce the cost associated to the policy (see Smulders and De Nooij (2003); Gans (2012) for theory and Otto et al. (2007), Bosetti et al. (2011) and Kriegler et al. (2014) for applied modelling results). Second, the TFP term A_t in equation (1) does not only capture the effect of innovation. In discussing empirical measures of TFP, Hulten (2001) points out that "many factors may cause this shift [in TFP]: technical innovations, organizational and institutional changes, shifts in societal attitudes, fluctuations in demand, changes in factor shares, omitted variables, and measurement errors. The residual [TFP] should not be equated with technical change, although it often is" (Hulten 2001, p. 40). As an example of an alternative interpretation of TFP, Huo and Ríos-Rull (2013) explain the sharp drops in TFP experienced in developed countries during the post 2007-2008 recession from the demand side - the households desire to spend - rather than using arguments related to technology. Another interesting example is related to a simple input-output model. When a fraction α of output is used as intermediate in production, the gap between the direct capital and labour technical productivity and aggregate output is due to an input-output multiplier. Introducing intermediate goods use in a production function without TFP:

$$Y_t = F(L_t, K_t) + \alpha Y_t,$$

where Y_t is gross output, we have that

$$Y_t = \frac{1}{1-\alpha} F(L_t, K_t) = A(\alpha)\, F(L_t, K_t). \tag{2}$$

Therefore it is inaccurate to refer to A_t as innovation. What distinguishes innovation from other TFP components is the dynamic nature. The effectiveness of current research depends on the accumulated stock of past knowledge, as suggested by the "standing on the shoulders of giants" argument (e.g. Scotchmer, 1991). Moreover, about the adoption of specific technologies, there might be lock-in effects that induce the crowding-in of investment towards the same technology type in the future. The learning-by-doing argument and induced-innovation theory are as well characterized by dynamic effects and hysteresis. These arguments make clear that the full potential of innovation is only captured if treated as an endogenous variable. Using a compact formulation, the growth rate g_{At} is a function of other variables in the model like the investment in R&D activities, the existing level of technology and factor prices (or factor shares), so that $g_{At} = g_A(p_F, RD_t, A_t)$, where RD_t is R&D expenditures and p_F is an index of production costs. For the case technological progress is modeled endogenously, it is crucial to have a more detailed representation of innovation and to identify which research activity drives the endogenous response to demand and factor variables. In order to do that, CGE models with endogenous technologies are based on microfounded theories of endogenous growth that explicitly model the economic incentives behind research and adoption activities. The next section will present the endogenous growth literature that provided sound theoretical foundations to the introduction of innovation in CGE models. Here we offer an overview of how innovation interacts with production and consumption in a general equilibrium setting and present some basic definitions of different types of innovation.

Figure 1 is a detailed representation of technological progress in a multi-sector economy. The diagram shows the most important drivers of firms' production efficiency within a sector. At the centre of the graph, the circle stands for the set of production technologies in a sector i, characterised by a level of efficiency in employing production inputs. Referring to the production function (1), the circle "Production efficiency" means to represent the part of A_t which is directly depending on firms technological level. It captures several factors as, for instance, technology embodied into machines and equipment used in the production process, experience and know-how for specific production activities, the stock of intangible assets (knowledge stock) as well as the labour's stock of human capital.

Innovation occurs when the firm develops, or simply adopts, more effective production processes, organization structures and products. Ideas are sometimes acquired from external sources and integrated in the firm's business and sometimes they are developed directly by the firm through R&D activities. In the latter case, the innovating firm can direct R&D activities towards distinct aspects of the firm business and pursue competitive gains. One type of innovation aims to make product quality improvements, introducing substantial modifications in product's technical characteristics and applications. The result of this form of innovation, called product innovation, is a substantially new product that replaces old versions with a higher quality one, or introduces a new variety of a good or service. The incentive to develop a higher quality or new product lies on the consumers' willingness to pay for it. The innovator aims to boost revenues and profits are raised by charging a higher price that matches the increase in the product quality (but when this is not possible, rent spillovers arise). Whereas product innovation

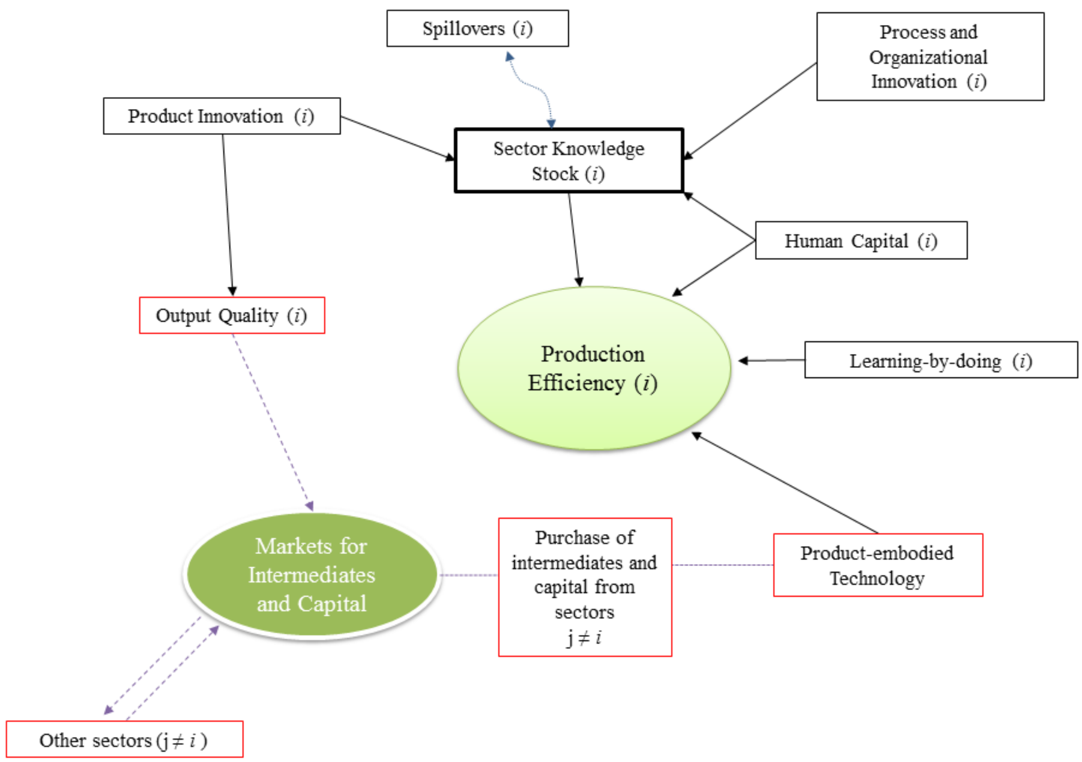

Figure 1: Technological progress in a multi-sector economy

delivers a new product line, there is an expansion in production together with profits. Under the assumption of consumer preferences characterised by "love for variety" (Dixit and Stiglitz, 1977), the introduction of a new good or service induces higher final demand and utility.

Innovation might as well improve profitability by boosting inputs efficiency without changing the product offering. In this case the firm is able to produce the same amount of goods or services with less inputs. Process innovation leads to higher profit margins and it gives the firm room for charging lower prices and for potentially expanding its market share at the expenses of competitors. In most cases the expected profit from developing a process-related technology is linked to its cost-cutting effect. Some empirical studies found a relationship between firm size and process-related R&D activity (e.g. Klepper (1996) and Cohen and Klepper (1996)) because process-related technologies can only partially be protected by intellectual property rights and the firm prefers to keep the exclusive use of the technology, so that expected profits depend on the scale of production it is applied to. Otherwise, if perfect protection of intellectual property rights is guaranteed, these profits might include the rent from licensing the technology to other firms.

In modelling studies process innovation is represented as a factor affecting marginal costs and the sensitivity of profits to factor price changes. An important characteristic of process innovation is the positive relationship between the return of process-related R&D expenditures and the level of production costs. On the one hand, high costs might indicate sources of inefficiencies and process innovation be particularly effective in that case. Conversely, if a firm is already producing at low costs there might be little room for additional improvement because of technical and organisational constraints. On the other hand, the incentive to carry out process innovation is higher when inputs get more expensive.

To summarize, the incentive to invest in a unit of process-related technology that saves a fraction x of marginal costs is an increasing function of initial unit costs, UC, and the scale of production Y. Total cost savings from the adoption of a this technology, S, are $S = x \cdot UC \cdot Y$.

There are other types of innovation besides product and process innovation. One important example is organizational innovation. New ideas on the firm's organizational structure might unveil lines of intervention to boost competitiveness. In this case the efficiency improvement is achieved through changes in the company structure and the allocation of tasks and duties over the personnel. One example is the lean manufacturing system introduced in the automobile industry in the 20th century. Even if the distinction between process and organizational innovation is important in the microeconomic and management literature, these two types of innovation have very similar macroeconomic effects. Therefore organizational changes are just regarded as a special case of process-related technologies in the analysis of economy-wide effects of innovation.

R&D activities relative to innovation on products, processes and the organizational structure contribute to increase the stock of knowledge in the firm. Within a sector, knowledge spillovers might arise across firms that operate in a similar business. Knowledge is in fact a non-rival good that is only partially excludable and firms are able to increase their own knowledge stock by imitation of and inspiration from other firms' ideas, even under strict intellectual property rights. There are as well intertemporal spillovers: the effectiveness of current research is amplified by the stock of past knowledge.

Another potential driver of production efficiency is learning-by-doing. In Figure 1, learning-by-doing is a separate source of efficiency improvements from knowledge accumulation. Whereas the knowledge stock and induced innovation approach focus on research activities, learning-by-doing (or by-using) emphasises the role of experience in the achievement of higher production efficiency. In this case productivity benefits from the experience that each firm accumulates over time in carrying out a specific production process and producing a specific product. Learning-by-doing is a function of past production levels and is not necessarily dependent on the firm's innovation activity and employees' skills.

The last major driver of productivity is technology embodied into capital and equipment goods used by the firm. Moving from the one sector world to a general equilibrium representation of the economy with heterogeneous sectoral outputs, there are additional reasons to distinguish between different types of innovation. Griliches (1994) makes an instructive example. The airline and the aircraft industries are vertically integrated and while the latter sector massively invests in R&D, the other has low research expenditures. At a first glance this fact makes us puzzled about the high TFP growth in airline firms and the way more modest productivity increase in the aircraft industry. Once R&D is differentiated between product and process innovation, the puzzle is solved. The upstream sector carries out product innovation and the downstream sector purchases more productive airplanes and related equipments. Product innovation in the aircraft industry creates products with embodied higher quality, which boosts the TFP of the airline industry. As Aghion and Howitt (2009) point out "more generally, making the proper quality adjustment would rise our estimate of TFP growth in upstream industries but lower in downstream industries. In aggregate, however, these two effects tend to wash out" (Aghion and Howitt, 2009 p. 110). The disaggregated multisector framework unveils technological interdependencies that are not important in the one sector model but might be relevant to address distributional issues.

Product-embodied technology should be kept distinct from the firm's internal innovation activities. The quality of machinery, equipment, transport vehicles, software and buildings depends on R&D investment carried out in their producing industries and not necessarily on the state of innovation that is internal to the adopting firm. For instance, the agriculture sector carries out little R&D activities but rather makes productivity gains by purchasing new machinery and equipment, which are produced in a different sector. By accounting only for sectoral R&D expenditures, the level of productivity in agriculture would be dramatically underestimated.

3 Microfoundations of Modelling Endogenous Innovation

In a one-sector general equilibrium model the innovation phase plays a key role in the modelling of technological progress. As Romer (1990) points out, base research leads to major fundamental discoveries but many applied technologies are developed by private enterprises. Endogenous growth theory grounds the microfoundation of technological change on the assumption that researchers are profit maximizing agents, setting the rate and direction of research effort while following profit incentives. In general equilibrium the incentive to patent the technology for a new good, to improve a product's quality or to develop cost-cutting technologies arise from the level of product demand and input prices. The owner of a patent is entitled to the stream of future profits from licensing the technology to production firms at a margin. In the lab-equipment model of Romer (1990), innovation is the process of expanding the set of available inputs. Researchers develop new types of durable goods (even if they fully depreciate each period) that are used in production together with labour: specialization is an engine for growth.

In models with expanding product varieties (i.e. Judd 1985) growth is instead driven by pure product innovation because of "love for variety" preferences, following Dixit and Stiglitz (1977). The offer of a new product on the market leads to an increase in final demand and an expansion in aggregate output. Consumers rise their utility by purchasing new goods and services that are developed through innovation. It results that the process innovation model with input specialization and the product innovation model with expanding goods varieties deliver equivalent results. In both cases, research and innovation allow to overcome decreasing marginal returns to capital accumulation and generate sustained growth. Moreover, in both type of models innovation is "horizontal" and product and process innovation can as well be interpreted as TFP.

Schumpeterian models, i.e. Aghion and Howitt (1992), depict a different type of product innovation in which R&D targets the quality of existing goods. Researchers have the incentive to deliver quality improvement because with "vertical innovation" the supplier of the highest quality in a product market obtains monopoly rights through patenting. Each new product replaces the existing lower-quality version and the innovator overtakes the incumbent monopolist (so the label "creative destruction"). Lab-equipment models and Schumpeterian models mostly differ because in the latter case firms face a direct competition on the same product line, whereas in the former type of model product innovation generates instead horizontal differentiation and innovative firms do not face direct competition from incumbents.

Innovators in Schumpeterian models face direct competition from future technologies, whereas in models of horizontal innovation the profitability of developing a new product is not influenced by other innovations. Even if these two classes of models differ with respect to the innovation setting, they still have a very similar behaviour. In fact, the distinction between different types of innovation in endogenous growth models is not crucial when it comes to aggregate productivity. In the lab-equipment model, product innovation in the production of intermediate goods leads to an expansion of production for a given amount of other inputs, i.e. labour, and their productivity increases as more machines get available. In Schumpeterian models, there are two vertically integrated sectors and product innovation conducted by upstream firms improves existing intermediate goods along the quality ladder. R&D increases intermediates-embodied productivity and the effect on aggregate productivity is equivalent to the case of process innovation in the downstream sector. The equivalence of product and process innovation for economic growth in a basic setting is also explained in Acemoglu (2009).

These different classes of endogenous growth models provide a suitable theoretical foundation for CGE modelling with endogenous innovation. As we will better discuss in the next section, CGE models make use of stylized representations of technology, e.g. knowledge stocks, that are nevertheless grounded on these theories and are supported by a microfoundation of the innovation incentives included in the model. In Nordhaus (2002) the accumulation of knowledge follows an innovation race between firms. In each period, the firm with the leading technology replaces old incumbents and gains positive profits. Models as Diao et al. (1996), Otto et al. (2007, 2008) and-Bretschger et al. (2011) directly refer to the Romer (1990)'s lab-equipment model. Other studies, as for instance Roeger et al. (2008) and Heggedal and Jacobsen (2011), have instead relied on the (semi-)endogenous growth model of Jones (1995) to account for the decreasing returns of R&D investment. A more general discussion is presented in the next section.

4 Drivers of Endogenous Innovation in CGE Models

In this section the most popular ways to introduce endogenous innovation into CGE models are critically reviewed and we highlight the role of different types of innovation in each family of CGE models. These works borrowed from the theoretical frameworks introduced in the previous section and needed to compromise between a sound microfundation and practical feasibility. Applied modellers had to face several challenges in adapting the theoretical framework to a setting for policy assessment. For instance, available data on aggregate innovation expenditures still have a limited coverage over sectors and countries. There is as well a scarcity of empirical estimates for some functions used in the theoretical literature, as the aggregate productivity of R&D expenditures and parameters describing the patenting stochastic process. Moreover, the microfoundation of innovation needs a for-

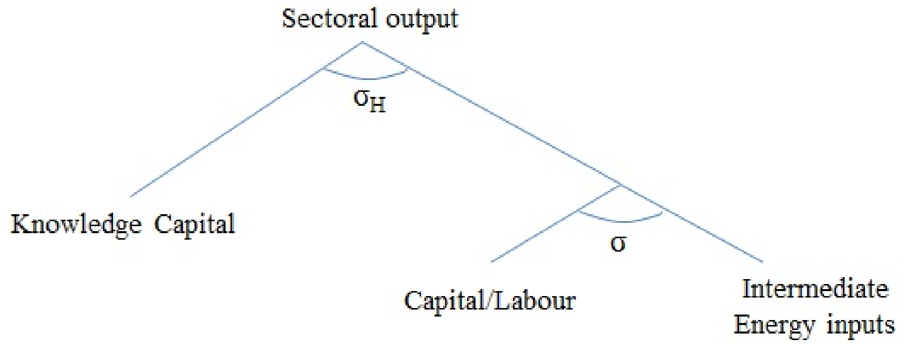

Figure 2: Knowledge stock and production nesting

ward looking setting: the incentive for researchers to innovate is linked to the expected payoff of future profits. Hurdles in solving large-scale CGE models with forward looking agents has limited the use such modelling setting in applied work (with few exceptions, i.e. Otto et al. 2007, 2008, Heggedal and Jacobsen 2011 and Bretschger et al. 2011).

4.1 Process innovation: Knowledge stock models

A top-down representation of technological change comprises knowledge stocks that accumulate similarly to physical capital (e.g. Goulder and Schneider, 1999; Sue Wing, 2003; Otto et al., 2008; Bosetti et al., 2009). The knowledge capital model has a long tradition in applied work - see for instance the early empirical work of Griliches (1979) - because of its simplicity, tractability and for having rather clear empirical counterpart (i.e. R&D expenditure or patent data). The knowledge stock specification is particularly convenient in a large-scale model with complex production structures. The stock of intangible assets is modelled as a special type of capital, so that innovation is introduced without bringing along computational and modeling issues.

With respect to the diagram in Figure 1, in this model the role of knowledge capital is central in determining technological efficiency in production. The knowledge stock enters the production function and it is located at the top of the production nesting (Figure 2). The innovation process is treated as investment in R&D that directly rises the productivity of physical inputs. The production of new knowledge through R&D activities is represented by the Innovation Possibility Frontier (IPF), usually an exponential function of R&D expenditures. In the knowledge stock model, R&D investment increases the productivity of physical inputs over time but not as a pure technology shifter like A_t in equation (1). Intangible assets are one input of the production function and in most common model specifications, e.g. Cobb-Douglas and CES, this assumption bounds the effects of innovation to the limits of decreasing marginal returns.

It is worth asking to which extent is process innovation depicted in this type of model. For instance, in the knowledge stock formulation, innovation has the major effect to increase the amount of output produced with a given level of physical inputs and there is no explicit output quality variation involved. But can investment in knowledge R&D be interpreted as process innovation? In order to answer this question we must go back to the economic incentives characterising process innovation (Section 2). An important feature of process innovation is the positive relationship between the marginal return of process-related R&D and production costs. High unitary costs can be interpreted as an indicator of inefficiency and cost-cutting measures are more effective when the firm is relatively inefficient. Moreover, process innovation should be more appealing when physical inputs are expensive. The second important characteristic of process innovation is related to the risk of imitation: the return of process-related R&D increases with the level of output. Therefore, investment in knowledge capital should be increasing in unitary costs and the level of output produced.

In the model, the firm carries out R&D investment I_t^H to increase the stock of available knowledge $H_t(I_t^H)$ at time t, with $H_t'(I_t^H) > 0$. Production output Y_t results from the use of a bundle of physical goods X_t (including labour, physical capital and energy) together with knowledge capital H_t, given a production technology $Y_t = \left[\alpha_H H_t (I_t^H)^{\rho_H} + (1-\alpha_H) F(X_t)^{\rho_H}\right]^{\frac{1}{\rho_H}}$. Intangible and physical inputs are often assumed to have a unitary elasticity of substitution (i.e. Goulder and Schneider (1999); Otto et al. (2008)), so that $Y_t = H_t (I_t^H)^{\alpha_H} F(X_t)^{1-\alpha_H}$. Here H measures the level of general productivity. Under the monopolistic market structure that arises because of innovation, the firm sets a price equal to $p_{Yt} = \mu c(R_{Ht}, p_{Ft})$, where p_{Ft} is the unit cost of the bundle of physical inputs and $\mu > 1$ is the price markup. R_{Ht} is the rental price of a unit of knowledge capital on the market.

The demand for knowledge capital rises with the cost of physical inputs, p_{Ft}. The optimal demand of knowledge capital results to be

$$H_t^* = \left(\frac{\alpha_H}{1-\alpha_H}\right)^{1-\alpha_H} \left(\frac{p_{Ft}}{R_{Ht}}\right)^{1-\alpha_H} Y_t, \tag{3}$$

and knowledge capital is increasing in p_F because of input substitution. The higher demand for H following a positive shock on p_F should be interpreted as the development and adoption of technologies that require a lower amount of physical inputs, including energy, to produce the same amount of output. Moreover, in (3) the optimal demand for knowledge capital increases with the scale of production. According to this analysis we might argue that the knowledge capital model represents the incentives underlying process innovation.

Output scale and input costs are in fact the two most important channels in the analysis of environmental taxes with endogenous knowledge capital. The effect of the introduction of an energy tax on H^* can be derived from (3):

$$\frac{\partial H_t^*}{\partial p_{Et}} / \frac{H_t^*}{p_{Et}} = (1-\alpha_H) \underbrace{\frac{\partial \left({}^{p_{Ft}}/_{R_{Ht}}\right)}{\partial p_{Et}} \frac{p_{Et}}{{}^{p_{Ft}}/_{R_{Ht}}}}_{+} + \underbrace{\frac{\partial Y_t}{\partial p_{Et}} \frac{p_{Et}}{Y_t}}_{-}. \tag{4}$$

The increase in production costs p_F due to the energy tax has two main effects on the demand for knowledge capital. The first term in (4) is the substitution effect, which leads to higher relative demand for intangible assets as the relative cost of physical input rises. The accumulation of knowledge follows profit incentives linked to production costs and the impact of the energy tax on innovation is increasing in the energy cost share in p_F. The second term is instead a second-order effect of the increase in p_F on final demand, given that higher production costs force firms to charge higher prices to consumers and demand falls. Theoretical studies, i.e. Smulders and De Nooij (2003) for energy and Gans (2012) for pollution, point out that the negative demand effect might dominate the positive shock on input costs. Such discouraging result is actually a finding of some applied modelling work based on the knowledge stock setting, i.e. Goulder and Schneider (1999) and Sue Wing (2003), in which climate policy actually decreases the overall rate of innovation.

4.2 Learning-by-doing

Together with process-related R&D and capital-embodied technology, experience is one extra-source of cost reduction and higher productivity. By working on a specific production process, the firm gains productivity because both workers and management reduce mistakes, fix inefficiencies and build up know-how. Learning-by-Doing (LbD) models aim to mimic the role of experience in productivity dynamics. The existence of LbD is a rationale for demand side policies in specific sectors. For instance, since the 1990s several governments have subsidized the adoption of renewable energy technologies in order to support the development of what was back then a rather immature industry. The strategy of demand-pull aims to lift the intensity of market penetration for these technologies and quickly achieve the benefits of LbD, with the target of reducing production costs.

In modelling work, LbD has been extensively employed in bottom-up models that have engineering-stile representation of production technologies. Bottom-up models of the energy sector have made use of LbD to endogenise technological progress specific to different energy sources (see Neij (2008) for a survey). This approach has the major strength to provide a clear identification of technical change, making it possible to carry out empirical studies on particular technologies and estimate their learning curves.

The learning process is commonly represented as a power function of the capital stock or the accumulated past production, called learning curves. A simple example is a cost function $C(.)$ that is decreasing in the level of experience

$$C(K_t) = C_0 K_t^{-\beta}, \tag{5}$$

where K_t is a cumulative measure of the production capacity installed up to time t (which can be either past output or current capital stock), β is the learning rate and C_0 measures the baseline level of costs. LbD is a mixture of process and organizational innovation, because it operates over the whole production process and it is strictly related to the reduction of production costs. In the empirical and theoretical literature of LbD, experience is indeed assumed to foster efficiency in production but leave product quality unaltered[1].

As also remarked in Gillingham et al. (2008), LbD is mostly a microeconomic concept that loses part of its original meaning once related to high levels of aggregation. High aggregation prevents from having heterogeneity in learning stages across technologies and the learning curve does not capture specific patterns of experience but rather the average effect of time on production efficiency, weighted by the actual growth rate of the economy or sector. Some top-down models include LbD together with R&D-driven technological progress (e.g. Bosetti et al., 2009 and Fischer and Newell, 2008),

[1] An additional effect of learning by doing is to reduce the number of production defects, therefore improving product quality. This effect of LbD has been so far considered as negligible in the literature. In a recent paper, Levitt et al. (2013) aim to fill this gap by providing empirical evidence on LbD quality-related effects using data from the automobile industry.

in order to separately capture innovation and the part of productivity improvements that strictly depend on R&D expenditures and that would not occur because of experience alone. Moreover, models like Fischer and Newell (2008) highlight the dependence of the learning effects from the knowledge stock: experience leads to sharper cost reductions if firms are well equipped in terms of knowledge and human capital.

These two different channels of cost reduction have to be clearly defined and empirically identified. LbD works *over time* through the stock of accumulated experience. Process-R&D induces new ideas to have more cost-efficient production through the work of specialized subgroups of the labour force (i.e. researchers), likely to have quicker and better results the higher is their budget funding for research activities. The latter channel is heavily dependent on dedicated funding and it may be regarded as a more uncertain driving force than LbD. In any case, the joint use of LbD and R&D innovation in top-down models brings along the risk of double counting the effects of endogenous technological change. This point is argued in details in Jacoby et al. (2006) and Nordhaus (2009).

4.3 Backstop technologies

Some technologies have groundbreaking effects once they become technically mature and affordable for firms and consumers. In environmental economics notable cases are nuclear fusion, Carbon Capture and Storage (CCS) and advanced renewable energy technologies. The availability of such technologies, commonly named backstop technologies, is critical for the design of optimal environmental policies and they acquire a special status in the modelling of innovation. The modeller knows the characteristics of the backstop and the technology is represented as a separate production or consumption function which is calibrated with current information on this particular technique. The backstop technology is usually not currently available on the market but the state of research is advanced enough to elicit expectations on the future deployment of the technology. Introducing backstop technologies in a modelling exercise is a purely ex-ante analysis because the modeller might have a belief about the probability of this technology to become available, but there is uncertainty about the exact timing this would occur. It is custom in the modelling literature to set a specific date $\bar{t}$ after which the backstop technology is available. Besides the timing issue, there is uncertainty upon its cost-effectiveness in the future. The adoption of non-fossil fuels - the backstop - very much depends on the market price of the dominant technology, i.e. fossil fuels. Even if the timing condition is satisfied, $t > \bar{t}$, the economic condition might not be and if $p_t^f < p_t^{nf}$ the non-fossil backstop is not adopted. For this reason, the modelling of backstop technologies is regarded as semi-endogenous, cf. Sue Wing (2006).

Backstop technologies do not necessarily belong to a specific class of innovations. A backstop might be a new product as well as a new production process. The distinction is even less clear from a modelling perspective, because some technologies show up as new products but have direct effects on production. The success of solar energy depends on parallel advances on the product side, making photovoltaic modules more efficient, and on the production process side, e.g. reducing the cost of producing solar cells. From a modelling perspective, solar power becomes competitive as soon as the price for generating one unit of electricity with this technology, p_{Et}^s, is lower or equal to the electricity price from a dominant technology, p_{Et}^f. An utility company that wants to produce electricity using photovoltaics has the opportunity to install a stock of solar panels characterized by embodied technical efficiency A_t^{PV} at a price p_t^{PV} per module:

$$p_{Et}^s = C(A_t^{PV}, w_t, p_t^{PV}), \tag{6}$$

where $C(A_t^{PV}, w_t, p_t^{PV})$ is the unit cost function for generating electricity from solar energy and w_t measure labour costs associated with operating solar installations. The index A_t^{PV} measures the energy conversion efficiency of the solar panel. The cost function C is decreasing in embodied efficiency, $C_A < 0$, and is increasing in p_t^{PV}, so that $C_p > 0$. Both product and process innovation in the photovoltaic industry are important for the utility company. Equation (6) shows that both a decrease in the purchasing cost of photovoltaics, p_t^{PV}, and the rise of embodied efficiency, A_t^s, lower the price p_{Et}^s and contribute to satisfy the condition for the solar technology to penetrate the market, that is $p_{Et}^s \leq p_{Et}^f$.

4.4 Product and Process Innovation in a Multisector Multicountry Framework

The non-rivalry and partial excludability of ideas are important features for policy assessment, in particular for the modelling of environmental policy. Technology externalities arise because of imitation and inspiration of new ideas from the existing stock of knowledge. At the firm level the incentive for R&D investment is reduced because of non-full appropriability and risk of imitation by competitors, having a clear negative effect on the research effort. However at higher levels of aggregation this result does not necessarily apply and knowledge spillovers across firms can potentially lead to a higher technological level compared to the full appropriability case. The social return of firm's R&D investment is higher than the private return and economists advocate for research subsidies to address this market failure. In CGE models this phenomenon is caught by a multiplier applied to the production function or to the IPF. In a multisector framework, the knowledge spillover multiplier $\bar{H}_t$ represents the non-excludable knowledge that belongs to sectoral (or firm-level) innovation activities, H_{jt}, and that spills to the economy-wide level as:

$$\bar{H}_t = \sum_j \beta_j H_{jt}, \tag{7}$$

with a coefficient β_j that measures the degree of spillover of sectoral knowledge to the economy-wide stock of ideas. Sectoral production functions are augmented with the spillover multiplier $\bar{H}_t$ as follows:

$$Y_{jt} = \left(\bar{H}_t\right)^{\gamma_j} F(H_{jt}, L_{jt}, K_{jt}, \{X_{ij,t}\}_{i=1}^{J}). \tag{8}$$

where the coefficient γ_j controls the feedback effect of economy-wide non-excludable knowledge on the productivity of each sector. We introduce an input-output structure typical of multisector models, where $X_{ij,t}$ are intermediate goods produced by a sector i and used in production of sector j.

This specification is one example of how knowledge spillovers are included in applied modelling (alternatively, spillovers could enter the IPF of sectoral knowledge accumulation). The integration of knowledge externalities is critical for model outcomes about research investment and welfare effects (cf. Löschel, 2002 and Gillingham et al., 2008) and it is very important to have accurate estimates of the parameters - as β_j and γ_j - that regulate the effects of knowledge spillovers. In fact, the magniture of technology externalities is very much an empirical question, cf. Hall et al. (2009). For instance, the benefits from knowledge spillovers depends on the level of aggregation and on crowding-out effects. Spillovers might be limited because some technologies are sector-specific and have low imitation appeal for firms in other sectors. Moreover, the estimate of social returns of innovation should also take into account the potential crowding out induced by policy support on specific technologies, i.e. R&D subsidies on green technologies, with respect to investment in other fields of research[2].

Technology spillovers are more related to the creation and innovation stages of technological change than to diffusion. Equation (7) is based on the knowledge stock model, where the level of spillovers only depends on R&D and innovation activities and not on expenditures on technology adoption, as for instance investment in capital goods. Non-excludable knowledge falls as “manna from heaven” on sectoral productivity. We might instead

[2]On this point we refer to Popp, 2006 for a more complete discussion.

argue that technology diffusion, through product-embodied technology, is a major driver of technological advancements. Product-embodied technology is another case in which the impact of a sector's R&D is not limited to the innovator's balance sheet but, differently from knowledge spillovers, not necessarily there are market imperfections involved. Consider the following example. The automobile sector engages in R&D activities and produces a new car engine based on a technology that lowers fuel consumption significantly. This result of product innovation potentially allows all other sectors to reduce their level of fuel demand after they acquire this new technology for transportation. In sectors with high intensity in transportation equipment the piece of innovation has significant cost-saving effects, but they have not performed any in-house R&D in the first place.

Back to equation (8), in a multisector knowledge stock model the effect of sector i's process innovation is distinct from knowledge spillovers. Process innovation in sector i reduces the price of intermediate goods, P_{it}, and it has a first-order effect on the cost function of firms in sector j. A similar argument might apply to the effects of product innovation performed in sector i. By adding a quality component to the production function as

$$Y_{jt} = \left(\bar{H}_t\right)^{\gamma_j} F(H_{jt}, L_{jt}, K_{jt}, \{q_{it}X_{ij,t}\}_{i=1}^{J}), \tag{9}$$

the quality index q_{it} has an impact on cost minimization of sector j that is equivalent to a reduction in P_{it} due to process innovation. Cost reductions and product-embodied technologies originated in other sectors are foundamentally different from pure knowledge spillovers. Sector j cannot benefit from innovation in sector i if no $X_{ij,t}$ is used in production, whereas in the standard modelling of knowledge spillovers the magniture of knowledge externalities does not depend on actual adoption of specific technologies.

The concept of technology adoption and product-embodied technology is not new in CGE analysis. A strand of the literature, e.g. van Meijl and van Tongeren (1999), Hübler (2011); Hübler et al. (2012) and Parrado and

De Cian (2014) has analysed the implications of international technology transfers due to technological progress embodied in foreign direct investment or traded goods. Countries differ with respect to their level of innovation activities, stock of human capital and institutions. Therefore there is room for both knowledge spillovers and technology transfer from developed to developing countries. Multi-country CGE models provide a natural framework to understand the implications of international flows of technology for the design of climate policy.

Even within the same country, sectors are heterogeneous with respect to their degree of technological opportunities (Ngai and Samaniego, 2011). As a firm develops a new product technology, it makes it available on the market. The piece of technology is also purchased by firms in other sectors, in particular those who do not have sufficient internal resources for developing the same technology, as well as sectors that belong to economic activities too different to rely on imitation. In the previous example, this new technology is likely not to generate imitation outside of the automobile sector. A postal service firm would buy new wagons from the automobile innovator, rather than developing its own technology through internal research and there are no knowledge spillovers. The idea of interindustry technology flows has been first investigated empirically by Scherer (1982) and Griliches and Lichtenberg (1984). They argue that econometric models of R&D-driven productivity growth are misspecified if the role of embodied technology is omitted and they find that firms increase their efficiency in inputs use not only by implementing the results of internal R&D but also benefiting from the technology acquired from other sectors.

In multi-sector general equilibrium modelling, process innovation in one sector affects the rest of the economy through the cost channel. In case upstream firms carry out process-related R&D, there are efficiency improvements for all downstream sectors because intermediate goods are now cheaper. In macroeconomics, the literature about Investment-Specific Technological

Change (ISTC) has studied to which extent process innovation in the capital goods sector contributes to economic growth (e.g. Greenwood et al., 1997; Cummins and Violante, 2002; Ngai and Samaniego, 2009). In the one-sector model[3] commonly used in these studies, i.e. Greenwood et al. (1997), ISTC is a type of non-neutral technological change that affects investment goods only. Innovation makes the production of capital goods more efficient and in each period one unit of new equipments contributes more to the production of output. That is, the price of capital goods - in terms of output - declines over time as data shows. Similarly to our discussion of equation (9), the modelling of ISTC can as well be interpreted as product innovation on capital goods and results would remain unchanged. This is because quality is defined in a narrow sense as capital-augmenting technology that determines the cost of an effective unit of investment goods. Ngai and Samaniego (2009) extend the original results to a multi-sector model with input-output structure and find that the contribution of ISTC to explain observed economic growth is even larger than what previously found because the input-output multiplier amplifies the productivity enhancing effects of ISTC. Process-related R&D activities carried out in the capital goods sector lead to substantial improvements in aggregate productivity.

Multi-sector modelling, in particular applied CGE modelling, has instead difficulties in accounting for the general equilibrium effects of alternative definitions of product quality. This is partly due to data limitations and to the limits of modelling work in dealing with complex concepts like product quality. Yet, there are specific definitions of quality that are compatible with applied modelling and that have not been fully explored so far. One example is energy efficiency of capital goods. Most of the energy consumption by firms and households is due to the utilization of capital goods, as

[3]Under a standard sectoral classification used in official sectoral statistics (i.e. NACE), these models have only one sector. Yet in the economy represented there are two types of goods, an investment and a consumption good, so that the interpretation of two sectors is as well suitable.

machines, vehicles and heating and lighting of buildings. The embodied energy efficiency of these products has steadily risen over time because of R&D in the capital goods sector, which had a crucial contribution for the whole economy to lower its energy intensity over time. An important point is that higher energy prices induce firms and households to demand capital goods with higher quality, that is it fosters product - but not process - innovation. Economy-wide improvements in energy efficiency boost the profitability of product innovation in the capital goods sector. In a recent piece of work, Baccianti and Löschel (2014) constructed a multisector CGE model that combines energy-biased technological change with product innovation in the capital goods sector. Whereas process-related R&D reduces the price of equipment and induces an increase in energy usage in downstream sectors, product-related R&D has the effect to improve the embodied productivity of capital goods and to reduce energy consumption in the rest of the economy. Clearly, in this case product and process innovation respond differently to environmental policies and modest rebound effects arise with respect to energy consumption in the capital good sector.

5 Final Remarks

There have been significant advances in modelling endogenous technological progress in CGE models of environmental policy. The development of multicountry multisector general equilibrium models with endogenous productivity has allowed to evaluate the response of innovation to environmental policies. These studies have offered new insights and results on the effectiveness and costs related to environmental policy in the long run, given the possibility of research and innovation to intervene on major economic variables. Yet the state of the art is rather rough in modelling the innovation process. In reality, R&D activities target different aspects of a firm's business, as product offering, production and organizational efficiency, but in most of models the representation of innovation is stylized. This paper has provided an overview of the literature and evaluated to which extent different types of innovation are integrated in the modelling of technological progress.

Process innovation plays the most important role in existing CGE models with endogenous innovation because modelling changes in input productivity is, in fact, rather straightforward. Knowledge capital and learning-by-doing models are typical examples of innovation models in which technological progress mainly affects production costs. Product differentiation and product quality have instead received less attention in the literature, because leaving the realm of homogeneous products brings analytical and computational complexities, as well as because simple representations of product quality deliver results that are equivalent to the ones obtained with process innovation. We have discussed the reasons why this is not necessarily the case under alternative definitions of product quality, as for instance product-embodied energy efficiency in a multisector (or multicountry) framework.

Future research should make the effort to open up the black box of innovation and better understand how the complexities of the innovation process can enrich CGE models. Other strands of economic literature suggest that product and process innovation deliver very different aggregate outcomes. Firm heterogeneity is one example, which has not been covered in our previous discussion because no existing CGE model with endogenous technology allows for firm heterogeneity and entry-exit. In the heterogeneous firms model of Atkeson and Burstein (2010) product innovation is associated to the entry of new firms in the market and it lowers aggregate productivity. On the contrary, process innovation lowers costs of individual firms and it has a positive effect on aggregate productivity.

Besides product innovation, there are other characteristics of R&D activities that are worth taking into account. Innovation can be drastic or incremental and R&D can be related to exploration or exploitation. The research strategy of firms might favour the status quo and avoid - or even be unable to achieve - the development and adoption of disruptive technologies. Environmental policy needs firms to promptly push forward the frontier of energy and pollution efficiency and to focus on the most promising technologies, even if disruptive. Innovation policy to support the achievement of environmental targets should set incentives to favour R&D on exploration and the development of drastic technologies. Akcigit and Kerr (2010) find that the decision to undertake exploration or exploitation R&D varies with firm size and smaller firms have a higher incentive to invest in the development of new products. This is only one potential direction of interesting research offered by looking into the details of the innovation process.

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Project Information

Welfare, Wealth and Work for Europe

A European research consortium is working on the analytical foundations for a socio-ecological transition

Abstract

Europe needs change. The financial crisis has exposed long-neglected deficiencies in the present growth path, most visibly in the areas of unemployment and public debt. At the same time, Europe has to cope with new challenges, ranging from globalisation and demographic shifts to new technologies and ecological challenges. Under the title of Welfare, Wealth and Work for Europe – WWWforEurope – a European research consortium is laying the analytical foundation for a new development strategy that will enable a socio-ecological transition to high levels of employment, social inclusion, gender equity and environmental sustainability. The four-year research project within the 7th Framework Programme funded by the European Commission was launched in April 2012. The consortium brings together researchers from 34 scientific institutions in 12 European countries and is coordinated by the Austrian Institute of Economic Research (WIFO). The project coordinator is Karl Aiginger, director of WIFO.

For details on WWWforEurope see: www.foreurope.eu

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